Computational and Physical Aspects of UAV Vortical Flows

Aerodynamic Issues Of Unmanned Air Vehicles
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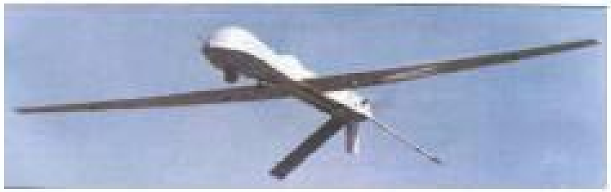
Broad Range of Mission Requirements & Concepts



UAV/HALE

UCAV's

MAV's

Prediction Challenges

Unconventional Design

Configuration

- Broad range of vehicle size
- Sensor-suite dictated
- High-aspect-ratio wings
- High-aspect-ratio swept wings
- Joined wings
- Delta wing platforms
  - -Moderate sweep ($\Lambda > 60^o$)
  - -Low sweep ($\Lambda < 60^o$)

Flow Conditions

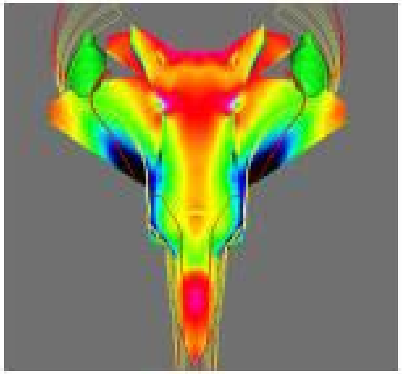
- Incompressible to transonic
- $10^4 < Re < 10^6$
- Laminar-transitional flows
- High-altitude
- Low drag aerodynamics

Extreme Flight Conditions

Viscous Flow Simulation for Air Vehicles

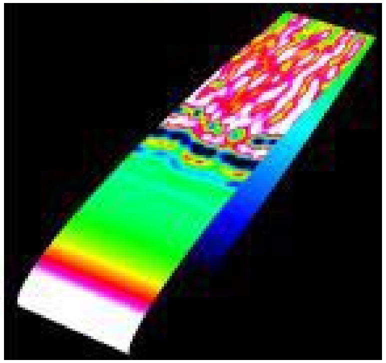
Modeling Hierarchy

Reynolds Averaged Navier-Stokes Eqs. (RANS)
- Full aircraft simulation
- 1or 2-equation models
- 2nd-order algorithms



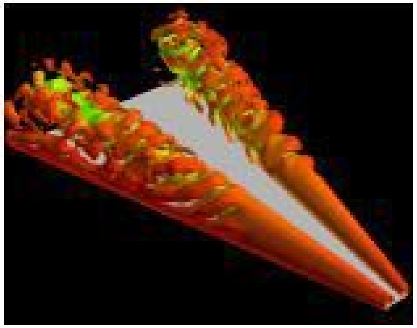
Hybrid approaches

Large-Eddy Simulation (LES)
- Component flow analysis
- Spatio-temporal turbulent large-scale structure
- Sub-grid scale models



High-order algorithms

Direct Numerical Simulation (DNS)
- Transitional flows
- Flow control devices
- Micro Air Vehicles (MAV's)



Flow Control

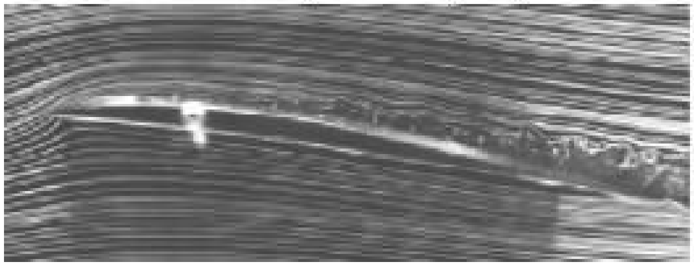
STEADY

UNSTEADY

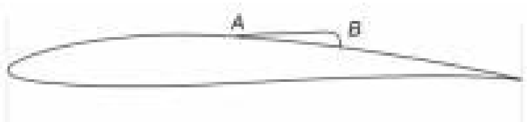
Prediction of Low-Re Airfoil Flows

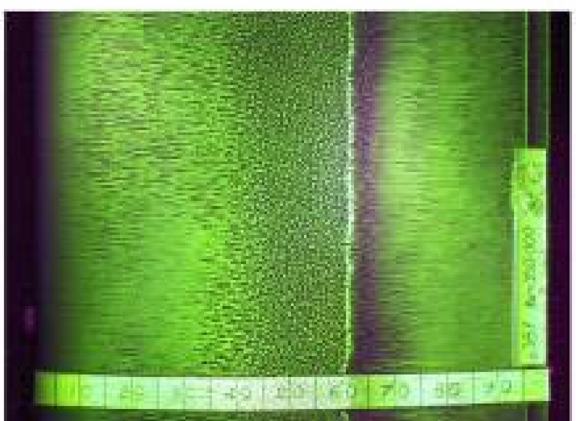
Experiment

Mueller et al, Re= 47,000, α = 8 °



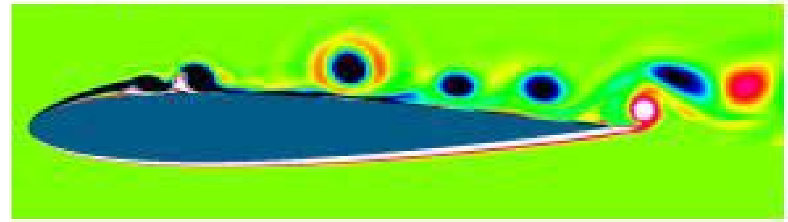
Selig et al, Re= 3.5×10^5, α = 2 °



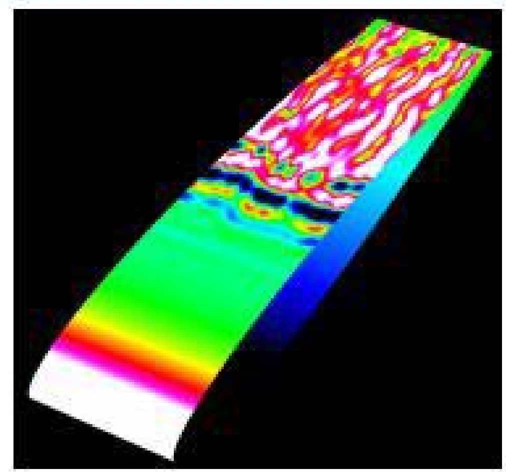


Computation

2-D

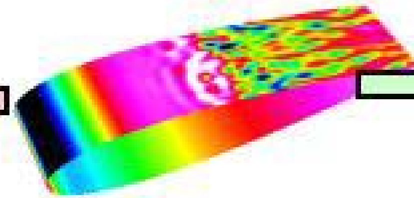


3-D



Re= 1.0×10^5, α = 5 °

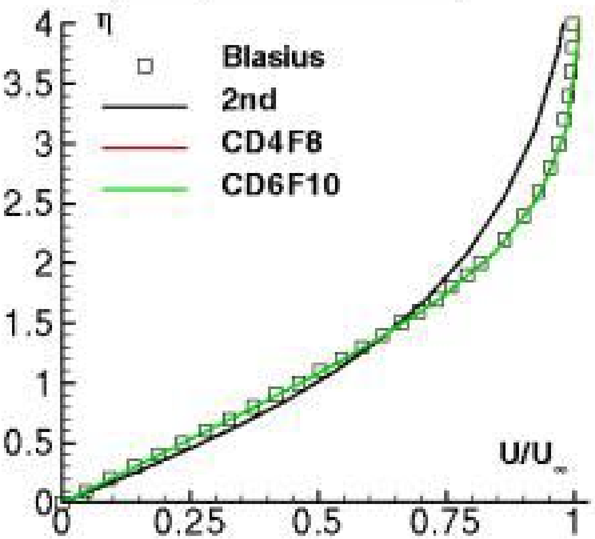
Impact of Scheme Accuracy on Prediction of Transitional Flows



Base flow prediction: Boundary layer

Growth of instabilities: Shear layer

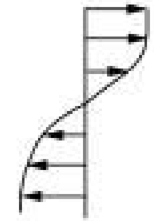
$Re_x = 1.45 \times 10^5$



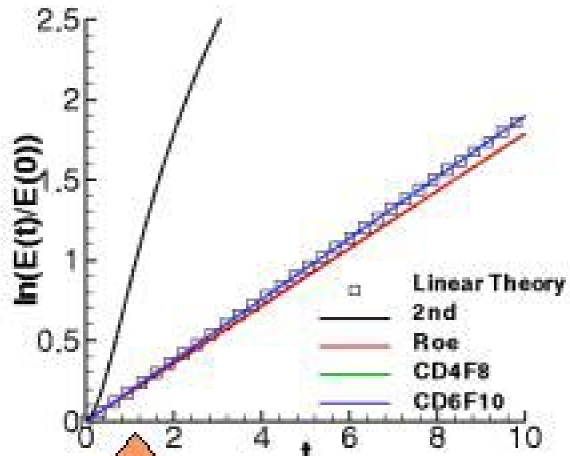
12 points in b/l

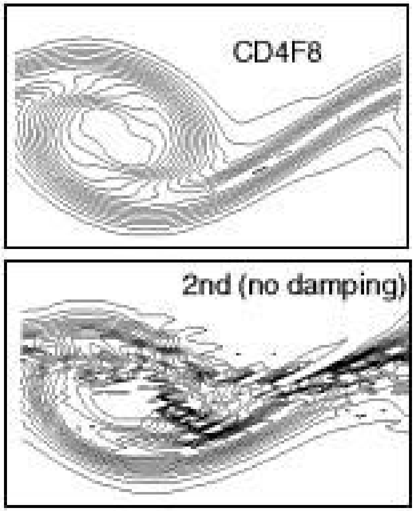
$U = 0.5\,(1 + \tanh(y))$

$M_\infty = 0.05$



Grid: 29 X 45

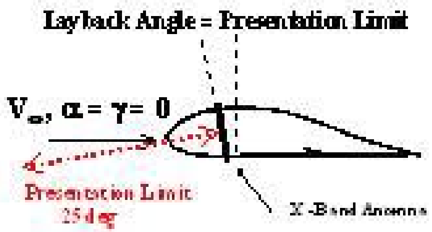


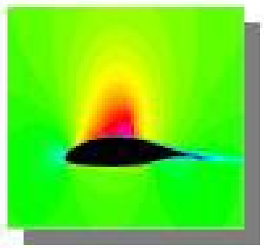


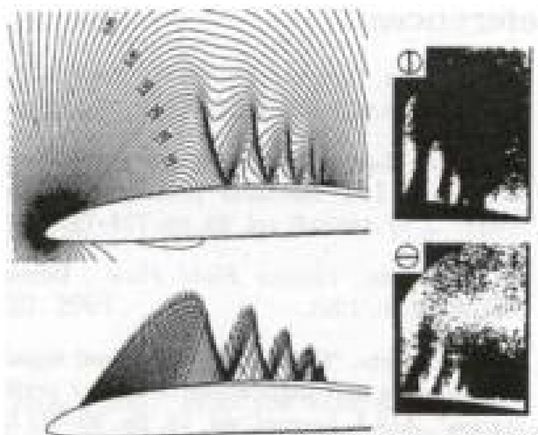
$$E(t) = \int_0^L \int_{-\infty}^{\infty} (\hat{u}^2 + \hat{v}^2)\,dy\,dx$$

Compressibility and 3-D Effects

Shock / B.L. Interactions

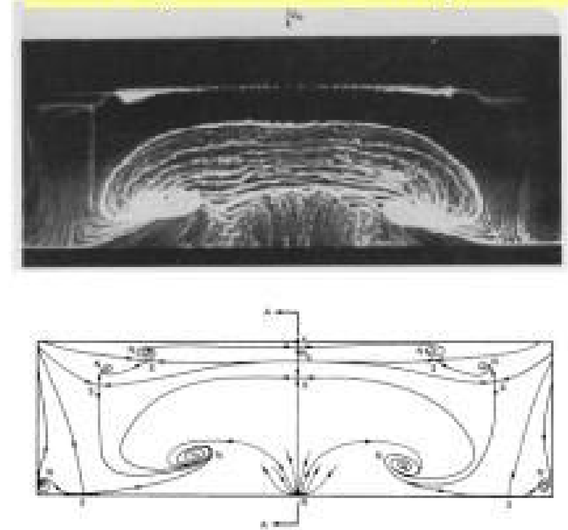




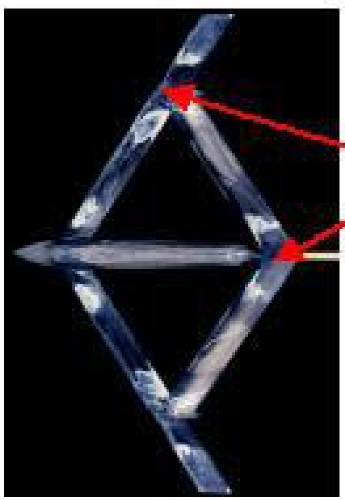


Drela, M=0.65, Re= 2 X 10^5

Complex 3-D Separation



Peake & Tobak



Juncture flows

Issues for the Accurate Prediction of Low-Re High-AR Wing Sections

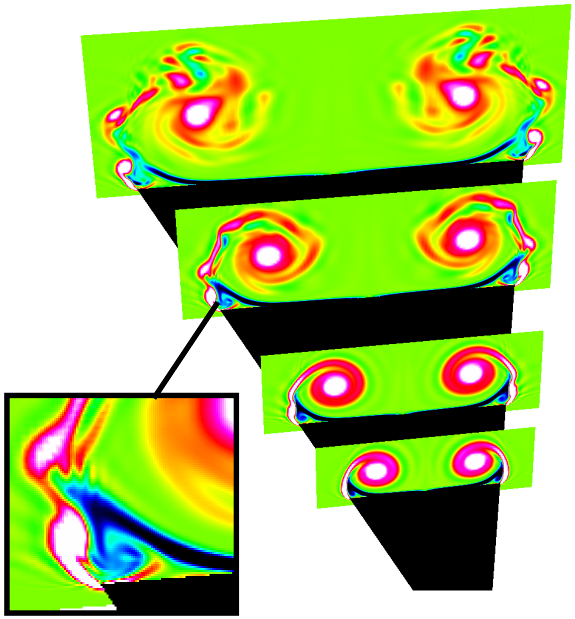
- *Separation* and *transition* must be captured accurately
- *High-resolution unsteady* tools required
- *RANS low-order* procedures not suitable for transitional flows
- Coupling of transition with body motion (implications for aeroelasticity and vehicle dynamics)
- *Crossflow instability* for swept wings
- Effect of gusts, crosswinds and aircraft dynamics
- Hysteresis effects
- Complex 3-D separation and juncture flows
- Transonic shock b/l interactions
- Surface heating effects on low-Re aerodynamics

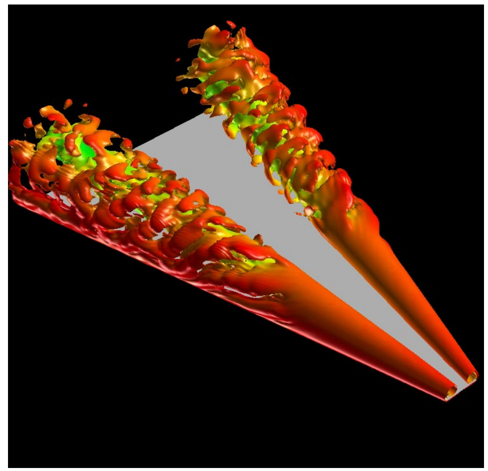
Delta Wing Platforms

Flow Challenges

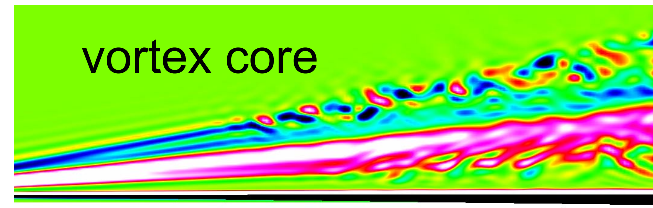
- Leading–edge vortex formation
- Feeding sheet structure
- Vortex wandering
- Vortex core dynamics
- Vortex asymmetries
- Interaction of multiple vortices
- Vortex breakdown & stall
- Hysteresis effects
- Dynamic motion effects
- Multiple time scales
- Reynolds number effects
- Unsteady loading (buffeting)
- Effect of wing platform leading and trailing edge shaping
- Shear-layer and boundary layer transition
- Flow structure for moderate sweep

Shear Layer Structure on Delta Wings



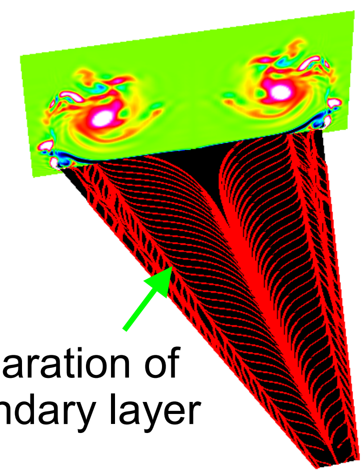


Λ = 75 ^{o}, Re = 50,000, α = 25 ^{o}



What is the origin of vortical sub-structures?
- Experimental disturbances
- Interaction of S/L with secondary flow, trailing-edge separation and breakdown
- Shear-layer instability modes
- Steady vs unsteady substructures

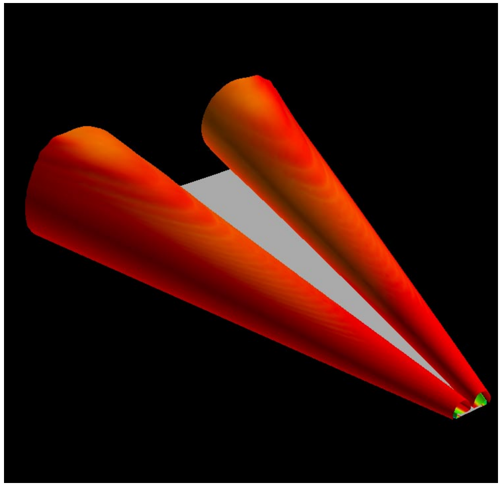
What is the relation of the surface flow pattern to the S/L transition process?



Laminar separation of
surface boundary layer

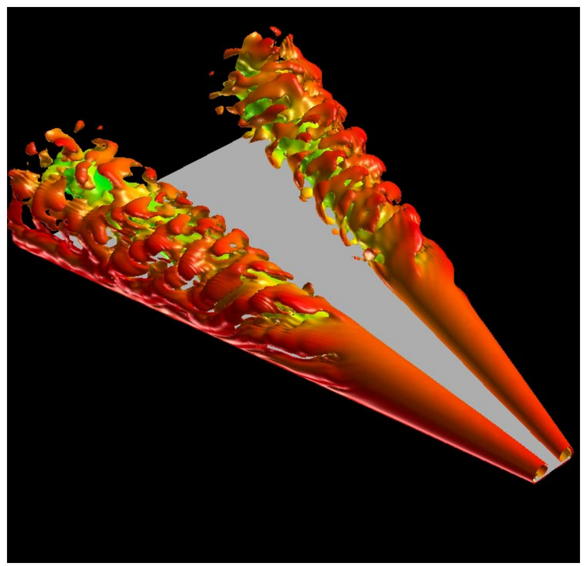
Moderate-Re Flows on Delta Wings: Evolution of Shear Layer

$\Lambda = 75^{o}$, $\alpha = 25^{o}$

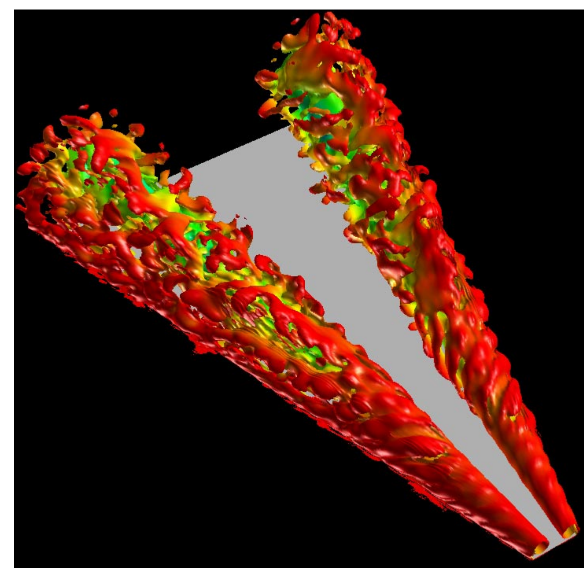


$Re = 10^{4}$

$Re = 5 \times 10^{4}$



$Re = 10^{5}$



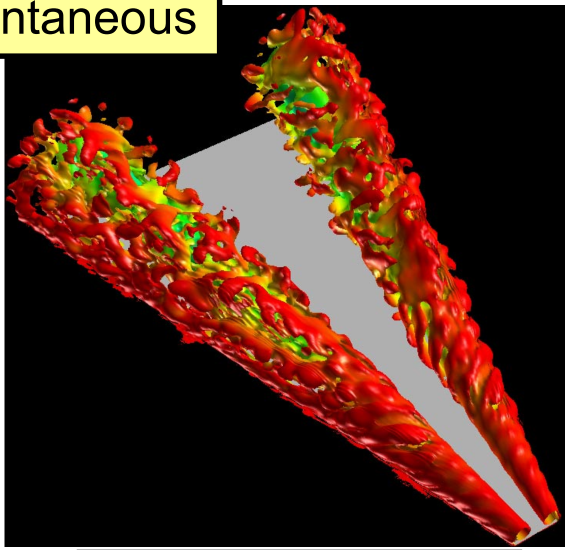
Increasing Re

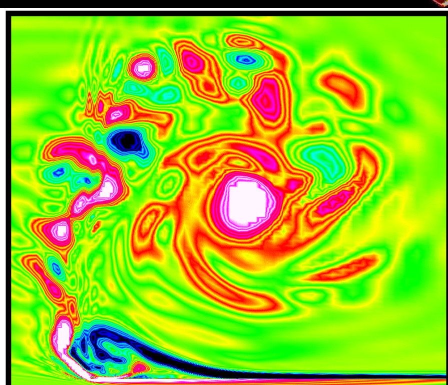
Complex flow field evolution in transitional regime

Instantaneous and Mean Representations of Transitional Shear Layer

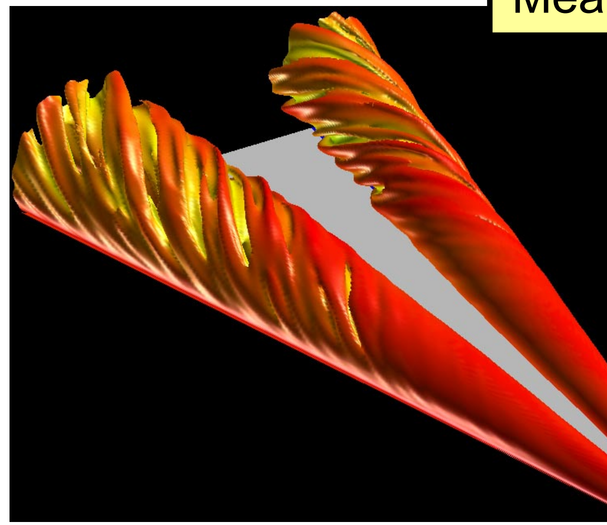
$\Lambda = 75^{\circ}$, Re = 100,000, $\alpha = 25^{\circ}$

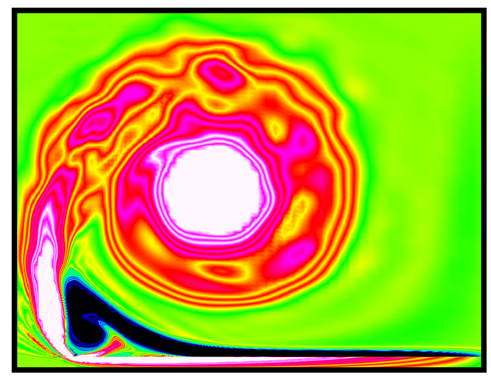
Instantaneous





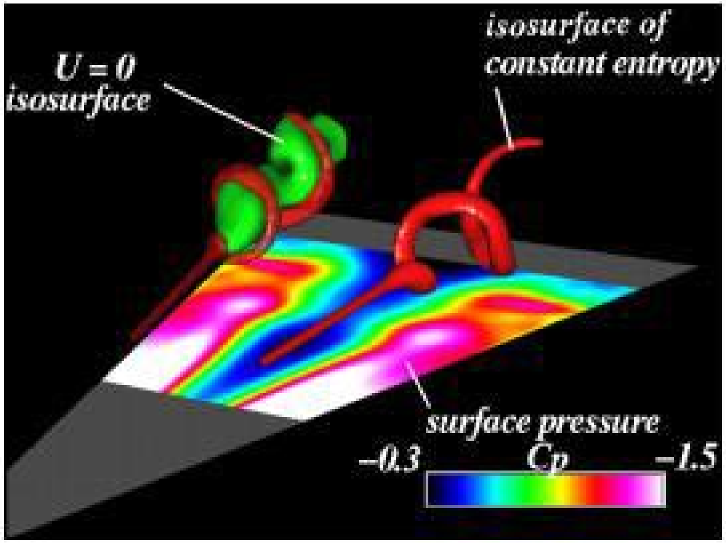
Mean





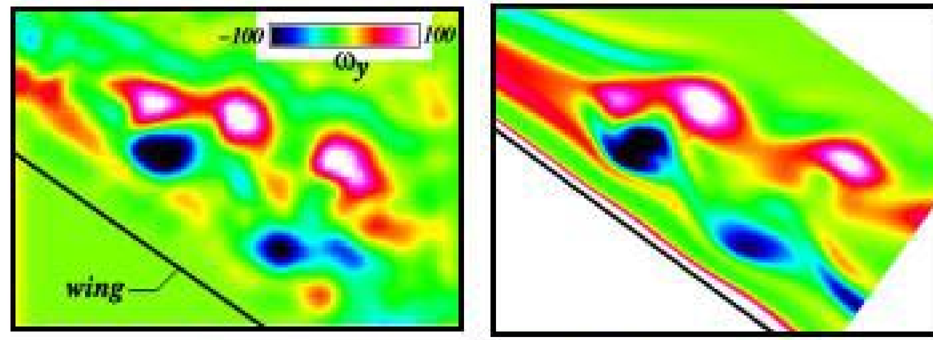
Are steady & unsteady sub-structures distinct phenomena or simply different representations of transitional/turbulent shear-layer dynamics ?

Physics of Vortex Breakdown

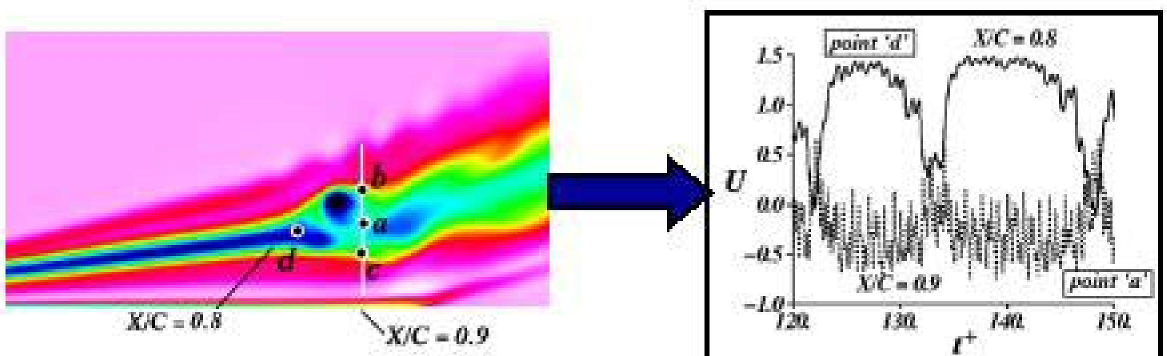


Experiment

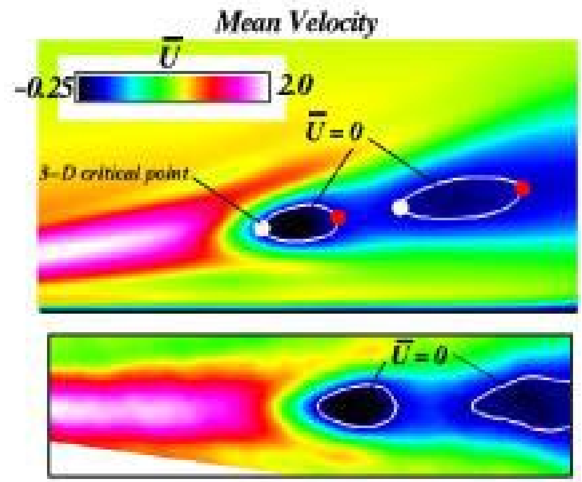
Computation



Instantaneous structure

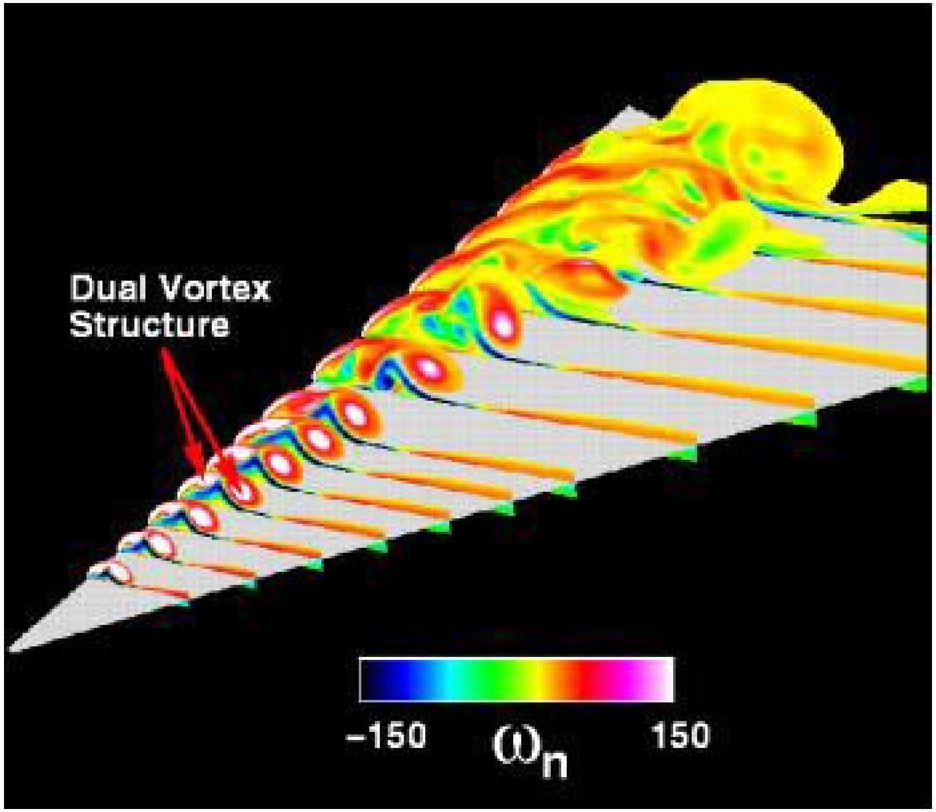


Breakdown fluctuations

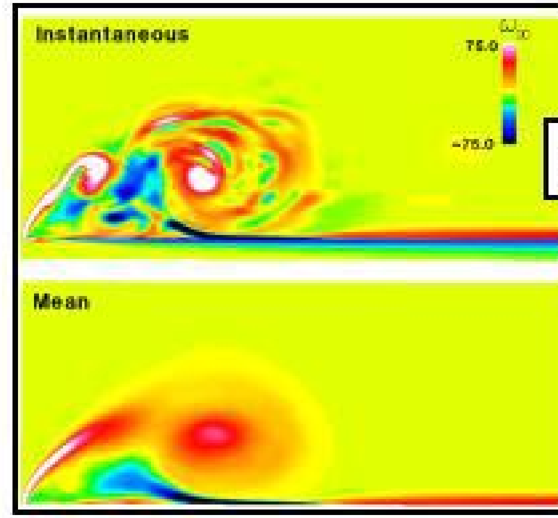


Mean Flow

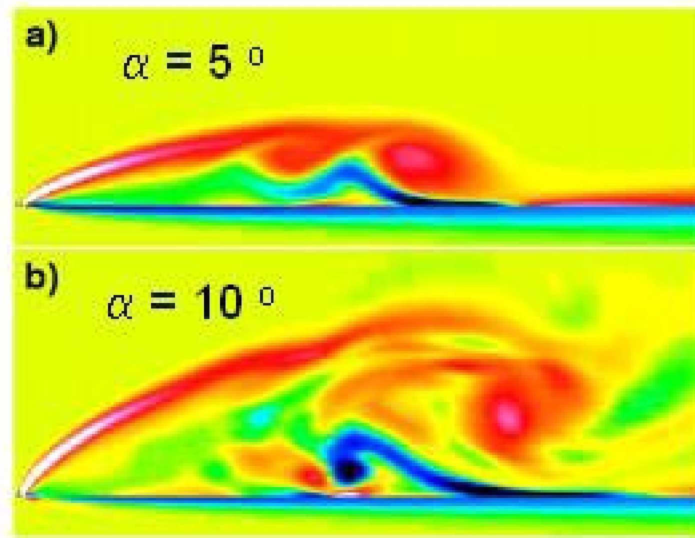
Delta Wing Flow Structure for Moderate Sweep Angles



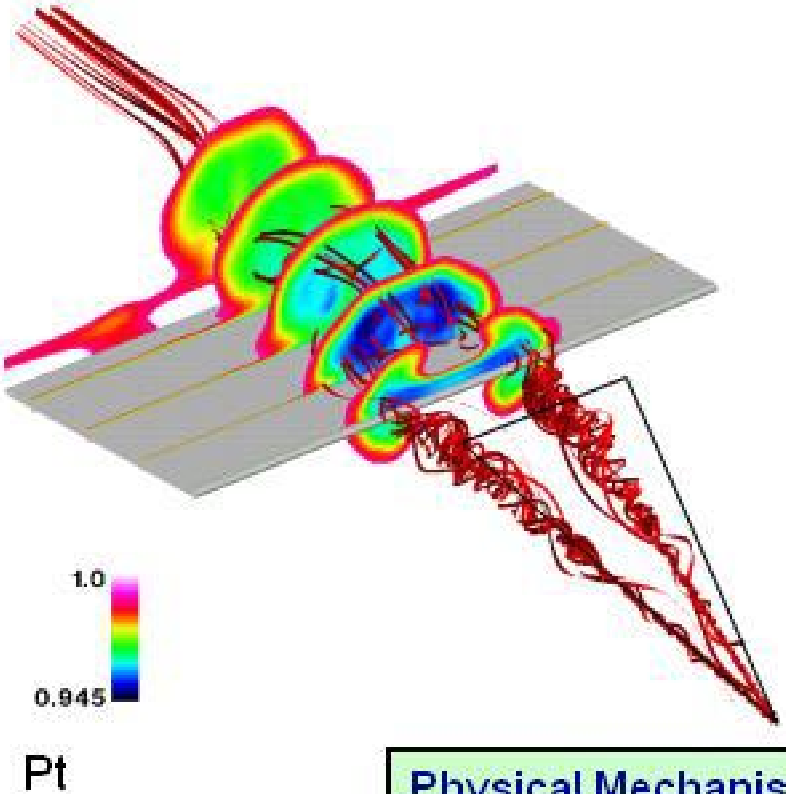
Λ = 50°, α = 10°, Re= 20,000

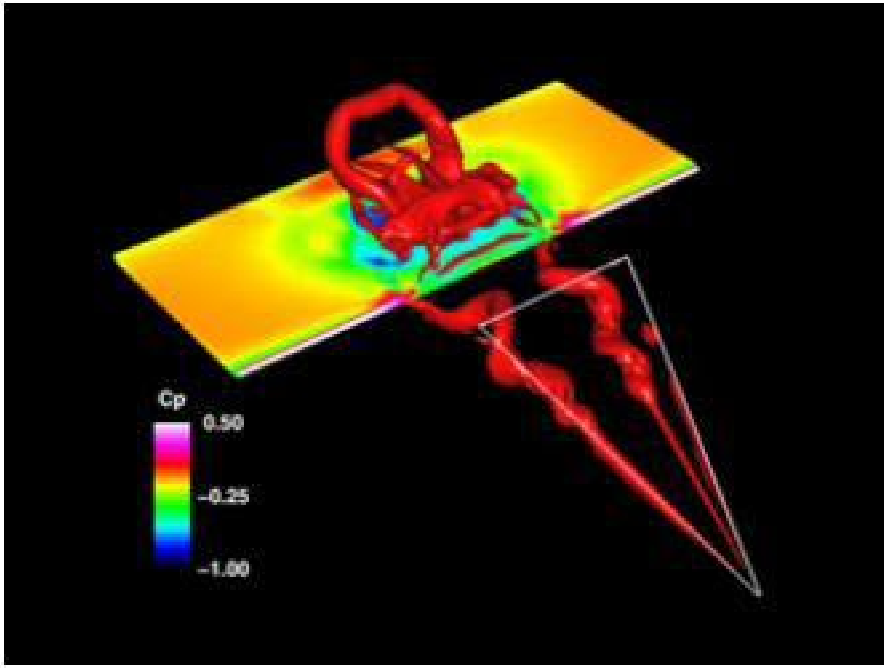


α = 15°



Physic of Vortex/Surface Interactions





Physical Mechanisms:
- spiral instability
- fin leading-edge separation
- breakdown fluctuations
- vortex distortion & splitting
- Feedback between breakdown and fin separation region

Some Key Issues

- Need to reinvigorate vortex flow research with emphasis on UAV applications
- Unconventional flight conditions/configurations demand combined experimental / numerical approaches
- Flows are inherently unsteady, possibly transitional and always three-dimensional
- High-fidelity unsteady numerical tools suitable for the nearly-incompressible to the transonic regimes are required
- Simulation of coupled phenomena is essential, *i.e.* fluid-structure interactions, flow control and vehicles dynamics
- High-fidelity tools needed to guide more affordable design approaches